Computer Simulation of a Geomagnetic Substorm

J. G. Lyon, S. H. Brecht, and J. D. Huba[a]
Science Applications, Inc., McLean, Virginia 22102

and

J. A. Fedder and P. J. Palmadesso
Geophysical and Plasma Dynamics Branch, Plasma Physics Division, Naval Research Laboratory, Washington, D. C. 20375
(Received 10 December 1980)

A global two-dimensional simulation of a substormlike process occurring in Earth's magnetosphere is presented. The results are consistent with an empirical substorm model—the neutral-line model. Specifically, the introduction of a southward interplanetary magnetic field forms an open magnetosphere. Subsequently, a substorm neutral line forms $\lesssim 15\, R_E$ in the magnetotail, and plasma sheet thinning and plasma acceleration occur. Eventually the substorm neutral line moves tailward toward its presubstorm position.

PACS numbers: 94.30.Lr

The understanding of geomagnetic substorms is one of the outstanding problems in space physics. Geomagnetic substorms produce major changes in the Earth's magnetosphere, lead to auroral displays, and can have an environmental impact (e.g., communications, power transmission). There is general agreement that substorms are powered by the solar wind as it flows around the Earth's magnetosphere. However, the energy transfer and dissipation mechanisms associated with substorms remain controversial.[1] Recent satellite measurements[2-4] and advances in theoretical plasma physics[5-7] lend support to a particular substorm model—the neutral-line model.[8-10] In this model, a southward interplanetary magnetic field (IMF) merges with the terrestrial field on the dayside magnetopause, adding magnetic flux to the magnetotail and raising the tail field stresses. When some (unknown) threshold is reached,[11] magnetic reconnection begins in the magnetotail near the Earth $[(10-20)R_E]$, energizing the substorm process. After sufficient energy has been released the neutral line moves rapidly tailward. As the neutral line moves past an observing point, high-speed flow which had been tailward becomes earthward.

In this Letter we present a global, two-dimensional (2D) simulation of this substorm process. The results lend strong support to the neutral-line model. Our code solves the following 2D time-dependent magnetohydrodynamic equations

$$\partial\rho/\partial t = -\nabla\cdot\rho\vec{v}$$

$$\partial(\rho\vec{v})/\partial t = -\nabla(\rho\vec{v}\vec{v}+P\vec{I}) + c^{-1}\vec{J}\times\vec{B}$$

$$\partial\epsilon/\partial t = -\nabla\cdot([\epsilon+P]\vec{v}) + \vec{J}\cdot\vec{E}$$

$$\partial\vec{B}/\partial t = -c\nabla\times\vec{E}$$

$$\nabla\times\vec{B} = (4\pi/c)\vec{J}$$

$$\eta\vec{J} = \vec{E} + c^{-1}(\vec{v}\times\vec{B}),$$

where ρ, $\vec{v}$, P, $\vec{B}$, $\vec{E}$, $\vec{J}$, and c are the mass density, velocity, gas pressure, magnetic field, electric field, current density, and speed of light, respectively. The quantity ϵ is the sum of the gas thermal and kinetic energies. The resistivity η has been set to zero in the calculations presented; however, numerical dissipation (i.e., resistivity) plays a large role in the calculations.

The code uses a leapfrog time-integration scheme and a 20th-order finite-difference approximation to the spatial derivatives. Flux-corrected transport[12] is used to provide the minimum possible numerical dissipation consistent with a solution showing no spurious extreme.

The computational grid is the x-z plane of the solar-magnetospheric coordinate system. In this system the Earth is at (0, 0), z is north-south, and x is positive toward the sun. The Earth is modeled as a small (<1 cell) cylindrical magnetic dipole extended in the y direction. The strength of the field is chosen to provide a bow shock approximately 10 R_E upwind from the Earth for the initial solar-wind parameters. The boundary conditions for the magnetic field in the z direction are those for an insulating region, i.e., $\nabla \cdot \vec{B} = 0$ and $\nabla \times \vec{B} = 0$. The boundary conditions for the hydrodynamic variables are as follows: The z boundary is treated as a hard wall; at the upwind ($+x$) boundary, the values of all variables are fixed to those of the inflowing solar wind; in the downwind direction, a transmitting boundary is used. The calculational mesh is 50 (along x) ×40 (along z). In order to avoid boundary effects (e.g., reflected waves), a stretched grid is used. The boundaries in the z direction are ~70 R_E from the Earth while the rear x boundary is ~100 R_E behind the Earth. The cell size near the earth is 1.5 R_E.

Initially, the grid is filled with a cold plasma ($T \sim 1$ eV/cm^3) with a density $n = 0.2$ cm^{-3}. An unmagnetized solar wind with a density $n = 5$ cm^{-3}, temperature $T = 10$ eV, velocity $V_{sw} = 400$ km/s and Mach number $M = 4$ is introduced at the far upwind edge of the grid. Eventually, a steady state is achieved and a short, teardrop-shaped "closed" magnetosphere is formed which is similar to our previous results.[13] Subsequently, a 2γ southward field is placed in the incoming solar wind. As the southward IMF contacts the northward geomagnetic field on the nose of the magnetosphere, steady-state reconnection occurs resulting in an open magnetosphere. The "resistivity" required for this phenomenon is numerical. Physically, an anomalous resistivity may arise in this region due to microturbulence (e.g., the lower-hybrid drift instability).[6] In order to prevent the dayside dipole field from being totally eroded by the reconnection process, we artificially convect magnetic flux from the nightside to the dayside, as required of any 2D model. In these calculations, the artificial convection electric field is assumed to be the solar wind electric field passed through an RC-type filter with a time constant of 30 min. We have run simulations with shorter and longer time constants. The change in the convection rate has very little effect on the results in the magnetotail.

The reconnected field lines are convected over the polar regions and added to the magnetotail, increasing its length and field strength. Figure 1 shows that magnetosphere after the 2γ field has been input for 50 min. The calculation looks remarkably like the generally accepted schematic of the magnetospheric field. The field strength in the tail lobes is ~20γ.

Shortly after this time, rapid reconnection spontaneously begins in the tail at a point $\lesssim 15$ R_E from the earth. Flow begins relatively slowly in the tailward direction, but after a period of 10 min high speeds ($\gtrsim 400$ km/s) are found ~30 R_E into the tail. The maximum flow velocity into the x point is about 100 km/s. High velocities in the x direction near the x point are not observed. There appears to be a gradual acceleration of plasma in the tailward direction caused by the release of field-line tension. During the period when reconnection commences and the plasma is initially accelerated to high speeds, there is also an indication that the plasma sheet thins in the (10–20) R_E range.

Figure 2 shows the magnetic field when the tail-

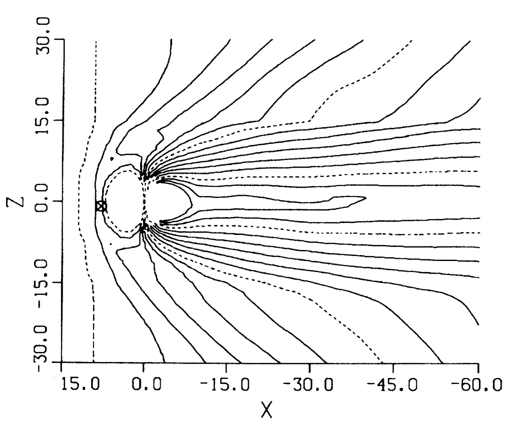

FIG. 1. Plot of vector potential (magnetic field lines) after a southward magnetic field has been incident for 1 h. Contours are equally spaced in vector potential. × marks the position of x points.

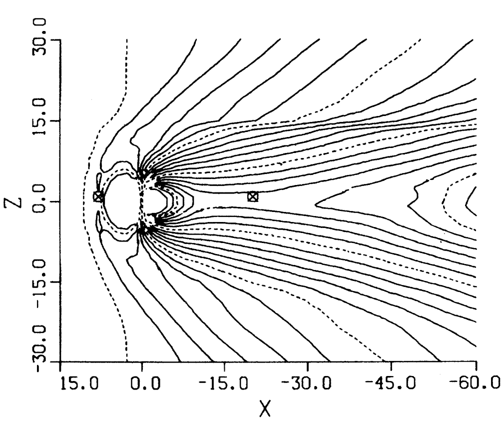

FIG. 2. Same as Fig. 1 except 20 min later at peak of tail reconnection.

ward flow and reconnection are at a maximum (~20 min after Fig. 1). The region of the highest-speed tailward flow coincides with the earthward half of the large magnetic island in the magnetotail. Plasma velocities in this region are in excess of 600 km/s. Almost coincident with the high-velocity region but extending further inward, the density has become almost a factor of 5 below the value which it had at the start of reconnection. Shortly after this time, the flow speed starts to decrease, and, simultaneously, the x point at $-15\ R_E$ begins to move tailward. Reconnection is still going on at the x point, indicated by fairly high z velocities inward to the x point.

Roughly 20 min later the magnetic field configuration appears as in Fig. 3. The x point has now moved tailward to $\sim -40\ R_E$, and tailward flow has almost ceased earthward of this point. Earthward flows are observed during this process but they never exceed 100 km/s. Figure 3 represents the end of a single cycle of relaxation oscillations. After this time, merging again commences near $-15\ R_E$ and the substormlike process reoccurs.

The simulations discussed are strikingly similar to the neutral line model for substorms originally presented by Hones[9] and McPherron, Russell, and Aubry.[10] The introduction of a southward IMF forms an open magnetosphere with an x point in the distant magnetotail. Subsequently, a substorm neutral line forms at $\lesssim 15\ R_E$ in the tail. Simultaneously, plasma sheet thinning (i.e., a decrease in density and plasma sheet width) and plasma acceleration occur. Eventually, the substorm neutral line moves tailward to

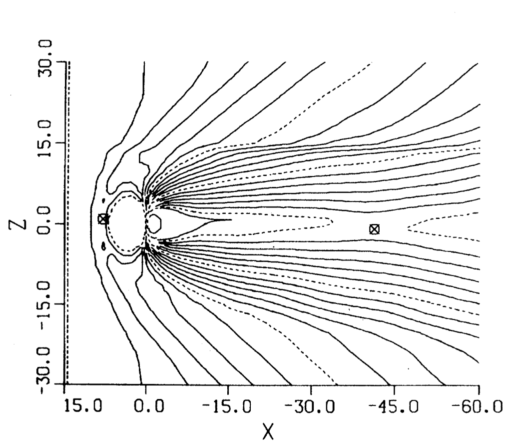

FIG. 3. Same as Figs. 1 and 2, but 20 min after Fig. 2. x point has moved tailward to approximately $-40\ R_E$ and one cycle of relaxation oscillations has finished.

its presubstorm position.

The time scale for the expansive phase of the simulated substorm is ~30 min, which is typical for real substorms. On the other hand, for real substorms the recovery phase lasts much longer (~1–2 h) than would be indicated by our relaxation oscillations. However, the constant 2γ southward field used in the simulations is probably an extreme condition. When the interplanetary field is strongly southward for long periods of time, continuous substorm activity is likely to occur. Furthermore, when we have discontinuously replaced the southward IMF by a 2γ northward field, the x point rapidly moved tailward and there was no evidence of reconnection recommencing in the near-Earth region.

An important feature of the simulations is the occurrence of reconnection at a position $\lesssim 15\ R_E$ tailward of the Earth. Our simulations shed light on why this region is preferred. It should be noted that while reconnection in the simulation is numerical (i.e., caused by a numerical diffusion process) the position where it occurs is *not* a numerical artifact. It is found that the current density at the substorm reconnection position increases more rapidly than anywhere else in the tail plasma sheet. In addition, the Poynting flux into this region is a local maximum, even before reconnection is clearly established. Thus, the onset region appears to be the nearest point to the Earth where the tail field can dominate over the Earth's dipole field.

One deficiency in our simulations is the absence of strong flows earthward of the reconnection region. High-speed flows toward the Earth are observed by satellites and are a crucial aspect of the neutral-line model. The lack of these flows may be ascribed, in part, to the fact that the reconnection process takes place because of numerical diffusion. In the code there is no Joule heating associated with numerical reconnection. Sato[5] has pointed out the importance of the pressure gradients produced by Joule heating in accelerating material along field lines out of the x point. Without this thermal energy input, our calculations must accelerate plasmas only by field-line tension. The asymmetry of the whole magnetotail about the x point clearly favors tailward acceleration. Furthermore, in the 2D model, earthward flowing plasma does not have the freedom to flow around the dipole field as it does in the 3D magnetosphere. Thus, it is not surprising that no strong earthward flows occur in the simulations.

Finally, we address the issue of resistivity. Based upon our observation that the current density is increasing most rapidly in the onset region, it is likely that a current driven microinstability is triggered in this region. This can lead to an anomalous resistivity which subsequently allows reconnection to proceed. The most promising instability at this time is the lower-hybrid drift instability.[6,7] We are presently improving our code to drastically reduce the numerical resistivity so that an anomalous resistivity, based upon the lower-hybrid drift instability, can be introduced for typical magnetotail conditions.

We have performed a 2D global simulation[14] of a substormlike process occurring in the Earth's magnetosphere. Our results are consistent with an empirical substorm model—the neutral-line model. Although the results are preliminary, they are very interesting and we are vigorously pursuing this avenue of research.

This research has been supported by the Office of Naval Research and the National Aeronautics and Space Administration.

[(a)]Present address: Geophysical and Plasma Dynamics Branch, Plasma Physics Division, Naval Research Laboratory, Washington, D. C. 20375.

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